AD-A157 323 THE MASS OF HOT SHOCKED CO IN ORION: FIRST OBSERVATIONS 1/1
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SPACE SCIENCES LAB G STACY ET AL. 24 JUN 85
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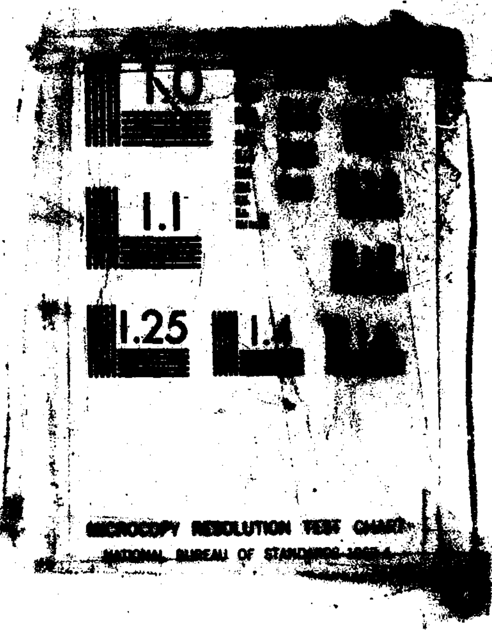
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Prepared for

SPACE DIVISION
AIR FORCE SYSTEMS COMMAND
Los Angeles Air Force Station
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This report was submitted by The Aerospace Corporation, El Segundo, CA 90245, under Contract No. F04701-83-C-0084 with the Space Division, P.O. Box 92960, Worldway Postal Center, Los Angeles, CA 90009. It was reviewed and approved for The Aerospace Corporation by H. R. Rugge, Director, Space Sciences Laboratory.

Lt David Barnaby, SD/YNCS, was the project officer for the Mission-Oriented Investigation and Experimentation (MOIE) Program.

This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
SD-TR-85-28

2. GOVT ACCESSION NO.
AD-A157323

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
THE MASS OF HOT, SHOCKED CO IN ORION: FIRST OBSERVATIONS OF THE J = 17 → J = 16 TRANSITION AT 153 MICRONS

5. TYPE OF REPORT & PERIOD COVERED

6. PERFORMING ORG. REPORT NUMBER
TR-0084A(5940-01)-3

7. AUTHOR(s)

G. Stacey, N. Kurtz, S. Smyers, M. Harwit, R. W. Russell, G. Melnick

8. CONTRACT OR GRANT NUMBER(s)
F04701-83-C-0084

9. PERFORMING ORGANIZATION NAME AND ADDRESS

The Aerospace Corporation
El Segundo, Calif. 90245

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS
Space Division
Los Angeles Air Force Station
Los Angeles, Calif. 90009-2960

12. REPORT DATE
24 June 1985

13. NUMBER OF PAGES
17

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)
Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Keywords:

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Abundances,
Far infrared.
Interferometer,
Interstellar molecules,
IR spectroscopy;
Molecular lines,
Orion Nebula,

to

10 to the -17th power

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

We have observed the Kleinmann-Low Nebula in Orion and detected the J = 17 → J = 16 transition of carbon monoxide at a flux level of 7 × 10^{-17} W cm^{-2}. Our best estimate for the total mass of hot, T ≳ 750 K, CO in the nebula is 8 × 10^{30} g. From this value we assess the total hydrogen mass at this temperature to be ~ 1.5 $M_\odot$. A puzzling apparent deficit of oxygen in the nebula is discussed.

W/sq cm

approx. Solar Mass

x 10 to the 30 power

approx. >

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PREFACE

We thank our colleague, Jim Houck, for loaning us his excellent offset guiding stage, used during these observations. We also appreciate helpful comments by Sara Beck, Steven Beckwith, Reinhard Genzel, Edwin Salpeter, Phil Solomon, and Pat Thaddeus, and thank the NASA Ames Research Center flight group for its excellent support.

CONTENTS

I. INTRODUCTION

We report here the first unambiguous detection of the $J = 17 \rightarrow J = 16$ transition at 153 μm in the interstellar medium. The contribution that this transition can make to our understanding of shocked interstellar gases is substantial since it falls into an unexplored gap that lies between transitions $J \rightarrow J - 1$ involving higher-energy upper states in the range from $J = 21$ to $J = 30$ studied by Watson et al. (1980) and Storey et al. (1981) and, on the other side, transitions from lower energy upper states $J = 6$ and $J = 4$, respectively, observed by Goldsmith et al. (1981) and Phillips, Kwan, and Huggins (1980). The lower-lying transitions are most strongly influenced by low-temperature gas. The higher-level transitions exhibiting rotational states around $J = 30$ are sensitive indicators of local density and temperature in the shocked region. The intermediate transitions involving rotational states around $J = 15$ are intimately associated with shocks, since the excitation temperature of these lines lies around 750 K; however, they are remarkably insensitive to temperature once the excitation temperature has been reached, and are also remarkably insensitive to density, particularly for density ranges associated with a molecular cloud such as the Kleinmann-Low Nebula (KL Nebula). The line strength is therefore a direct indicator of the total mass of carbon monoxide (CO) in shocked and postshocked regions and, by inference, can serve as an indicator of the total mass of shocked hydrogen in these regions. A direct measure of that mass is made difficult by interstellar dust, which readily absorbs the near-infrared H_2 emission but transmits the submillimeter CO radiation.

II. OBSERVATIONS

On the mornings of 18 and 22 September 1981, the KL Nebula in Orion was observed from aboard the Kuiper Airborne Observatory (KAO), flying at an altitude of 12.5 km. The instrument we used was a modification of our earlier liquid-helium-cooled grating spectrometer. It has been described elsewhere in more detail (Harwit <u>et al.</u> 1981). Briefly, however, the radiation from the telescope first passes through an interferometric stage and then enters the grating instrument that uses two stressed, gallium-doped, germanium detectors, capable of sensitive observations beyond 170 μm.

The interferometer is a two-beam device that effectively acts like a lamellar grating interferometer with just two lamellae. Light from the telescope is first focused onto a limiting aperture that determines the field of view in the sky along one direction--the direction along which the interference fringes are separated. A recollimating mirror follows this aperture and serves to image the primary mirror of the telescope onto two plane mirrors, in such a way that one semicircular half of the primary is imaged onto the stationary plane mirror while the other half is imaged onto the movable mirror. This pair of mirrors is used to produce an interferogram. The total travel of the movable mirror is 5 cm, so that the light-path difference induced is 10 cm. The theoretical resolution of such a device is 0.1 cm^{-1}. This corresponds to a velocity resolution of $\sim$ 500 km s^{-1} along the line of sight. We step the movable mirror through 32 successive positions and integrate for several seconds at each position to obtain the intensity in the central interference fringe at each separation.

This fringe of the recollimated radiation falls onto the entrance slit of the liquid-helium-cooled grating instrument used in all our earlier observations--an instrument of the type described by Houck and Ward (1979). While the field of view along one direction is determined by the limiting aperture of the interferometer stage, the field of view in the transverse direction is determined by the width of the grating entrance slit, the interferometer aperture being oversized along that direction. The overall field of view obtained in this way is rectangular and approximately 1' × 1', the field of view along one dimension being approximately 10% larger than along the other. Observations of the KL Nebula suggest an inflight noise equivalent power for the system, including all atmospheric and instrumental losses, amounting to roughly 3×10^{-13} W $Hz^{-1/2}$, at 153 μm for zero path difference in the interferometer.

The bandpass of the grating instrument is approximately 1 μm between half-power points. The free spectral range defined by the interferometer is 3.8 μm, and the separation between independent spectral elements is ~ 0.12 μm. Monochromatic radiation whose wavelength falls between two independent spectral elements will normally contribute part of its flux to one element and part to the adjacent element, making its line position uncertain by approximately 0.12 μm at 153 μm.

III. RESULTS

The spectrum obtained in observations of the KL Nebula is shown in Fig. 1. The absolute wavelength calibration of our instrument is currently uncertain to approximately 0.1 μm, and the peak of the radiation falls between 153.35 and 153.48 μm, the dominant component lying closer to the shorter wavelength. The line-to-continuum ratio at this wavelength is approximately 1:2 over the 0.24-μm wavelength interval defined by the two adjacent points. As explained below, this corresponds to a flux of 7×10^{-17} W cm^{-2} at Earth. Storey et al. (1981) find that the emission in the $J = 21 \rightarrow 20$ transition comes from a region whose diameter (FWHM) along a NW-SE scan is 1.5'. This would correspond to a line-emitting area on the sky roughly twice that of our beam, from which we conclude the total 153.3-μm CO flux from KL to be $\sim 1.4 \times 10^{-16}$ W cm^{-2}. Previous measurements carried out from the Lear Jet, with a field of view of 4' × 7', convince us that the total flux from the KL Nebula and its immediate surroundings is less than 3×10^{-16} W cm^{-2}, and that the radiation observed from the KAO is close to the total 153-μm line emission of the KL Nebula. We will see that this permits us to estimate the total amount of hot, shocked CO in this part of the Orion complex.

Measurements of the 153.3-μm CO emission were also attempted for a variety of other sources. In a previous flight on M17 on the KAO in May 1981, we tried to observe emission at this wavelength both at the infrared radiation peak and from the CS molecular emission region. Upper limits for this radiation are shown in Table 1. We also attempted observations of this CO line from NGC 7027. Here, radiation at a level of 10^{-16} W cm^{-2} may have been detected, but we can only be certain that the flux is not greater than this level. Finally, we report an upper limit also for NGC 2024.

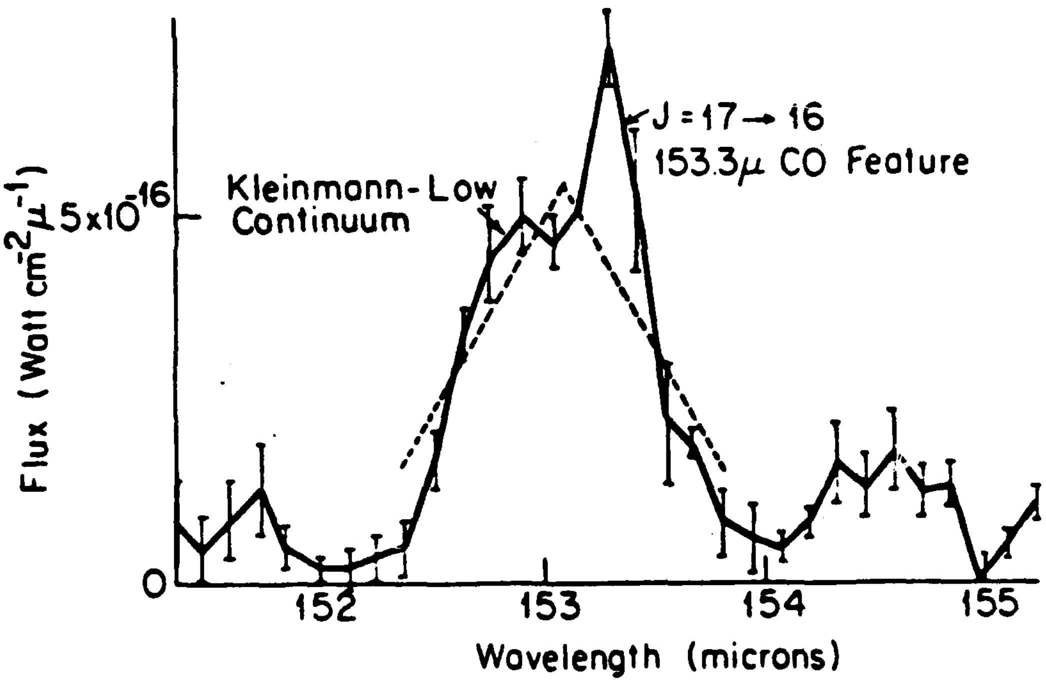

Fig. 1. The spectrum of the KL Nebula at 153 μm. If atmospheric absorption were entirely negligible, the continuum emission from the nebula would give rise to a purely triangular spectral response (dashed lines) peaking at ~ 153 μm with half-power points ~ 1 μm apart. Below 152.5 and above 153.9 μm, we expect no signal contribution. The plot shown here represents an average of four separate, triangularly apodized spectral runs, each of which exhibits the peak at 153.3 μm. Error bars indicate the standard error of the mean for these four spectral runs. The position on the sky viewed was the position of peak flux at 153.3 μm. However, since we are exhibiting the power spectrum here, all errors translate into positive values. The CO line is not resolved with our instrument.

Table 1. Results of 153-μm Observations in Search of CO Emission from Various Sources

Object	Flux (W cm^{-2})	Aircraft	Dates
KL observed 1' × 1'	7×10^{-17}	KAO[a]	Sep 1981
KL total estimated	$\sim 1.4 \times 10^{-17}$	KAO[b]	
4' × 7' field in Orion, centered on KL	$< 3 \times 10^{-16}$	Lear[c]	Nov 1979
M17 IR peak	$< 10^{-16}$	KAO	May 1981
M17 CS molecular region	$< 7 \times 10^{-17}$	KAO	May 1981
NGC 7027	$\lesssim 10^{-16}$	KAO	Sep 1980, May 1981
NGC 2024	$< 2 \times 10^{-16}$	Lear	Dec 1980

[a]KAO beam size 1' × 1'
[b]Estimated for a 2-$arcmin^2$ field of view
[c]Lear beam size 4' × 7'

IV. DISCUSSION

Watson et al. (1980) and Storey et al. (1981) suggested that the observed ntensities for the rotational lines they had detected were compatible with a vo-component model. One component had a temperature of 2000 K and a molecu- ar H_2 density $n(H_2) \sim 10^6$ cm^{-3}; the other had a temperature in the range from 00 to 1000 K and a density between 2 and 5×10^6 cm^{-3}. Recently, McKee, torey, and Watson (1982) computed the emissivities of different rotational ines of CO as a function of temperature and density. For the rotational ransition $J = 17 \rightarrow J = 16$, the emission rate per molecule is largely insensitive o both temperature and density, for temperatures above 500 K and densities bove 10^6 cm^{-3} (Fig. 2). The computed emission is cited as accurate to within factor of 30%. To that accuracy, the emission per molecule of CO can be aken to be 2×10^{-27} W sr^{-1} for number densities in excess of 10^6 cm^{-3} and or temperatures from 750 to 2000 K.

Werner et al. (1976) find the emission from the KL Nebula within a 1' eam to approximate a 70-K blackbody's radiation if the emissivity falls as $0/\lambda$, where the wavelength is measured in μm. On that basis our continuum lux at 153 μm should correspond to approximately 5×10^{-16} W cm^{-2} μm^{-1}. The andwidth of each of our spectral elements at this wavelength is 0.12 μm, and e see the line distributed between two adjacent elements at a strength just ver half the continuum (representing a line flux of 7×10^{-17} W cm^{-2} in the ine) in a 1' × 1' beam and, as discussed above, a total flux of 1.4×10^{-16} W m^{-2} from the KL Nebula. The strength of this line along with the results of lcKee, Storey, and Watson (1982) allow us to derive a CO column density of 4×10^{17} cm^{-2} in this region.

The overall accuracy of this value is roughly 50% and reflects uncer- ainty in a number of parameters of our new instrument, as well as limitations n the signal-to-noise ratio. This result agrees well with predictions made y Storey et al. (1981), coinciding, within our errors, with the value they alculate. If we assume the distance to the KL Nebula to be 500 pc, the flux t the nebula must be 3.4×10^{26} W sr^{-1}, corresponding to an emission of

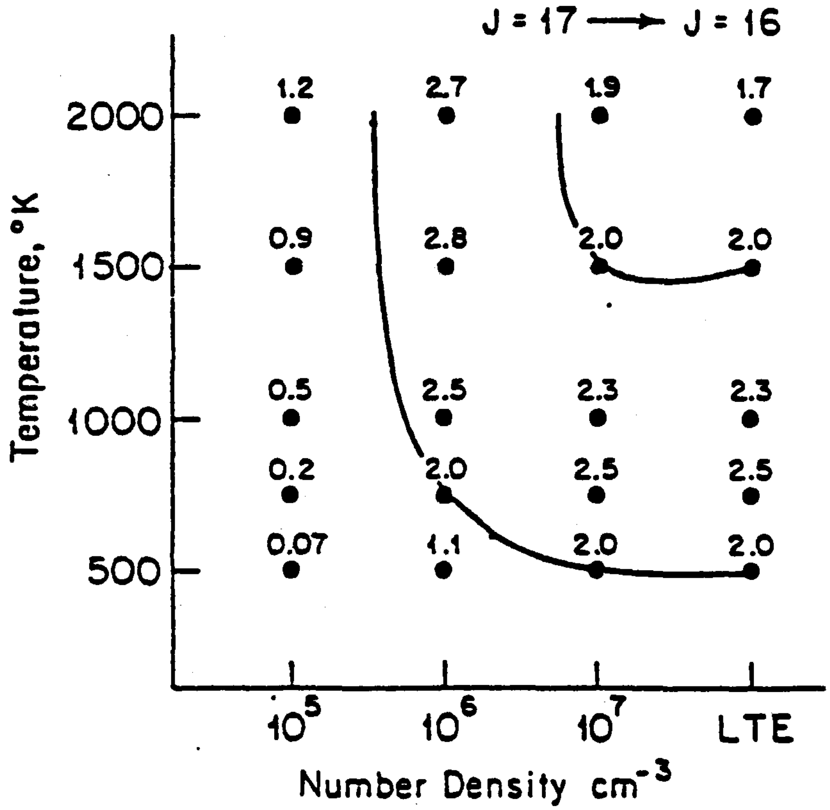

Fig. 2. Emission in Units of 10^{-27} W sr^{-1} molecule^{-1} (after McKee, Storey, and Watson 1982). The emission is plotted as a function of number density and temperature for the J = 17 → J = 16 transition at 153 μm.

$\sim 1.7 \times 10^{53}$ molecules or 8×10^{30} g of CO. If the ratio of number densities $n(CO)/n(H_2)$ is ε, then the number of hot, shocked H molecules corresponds to $\sim 1.7 \times 10^{53}\ \varepsilon^{-1}$, the mass of molecular H is $6 \times 10^{29}\ \varepsilon^{-1}$ g, and the depth of the $J = 17 \rightarrow 16$ emitting region is approximately $N(CO)/[n(H_2)\varepsilon]$ cm.

If one-quarter of all the C is in the fo.. of CO, as suggested by the observations of Storey et al. (1981), and if C is present in cosmic abundance, then $\varepsilon \sim 1.7 \times 10^{-4}$ and the mass of molecular H at a temperature $\gtrsim 750$ K is $\sim 3.5 \times 10^{33}$ g, roughly 1.5 $M_\odot$. This value of ε also implies that the depth of the CO-emitting region along the line of sight is $\sim 2 \times 10^{15}$ cm, corresponding to a thin, hot sheet, and is in agreement with the earlier conclusion of Beckwith et al. (1978).

This number is predicated on an emission rate of 2×10^{-27} W sr^{-1} molecule^{-1}, which, as Fig. 2 shows, holds true within ~ 30% over a temperature range between 750 and 2000 K and for $n_{H_2} \gtrsim 10^6$ cm^{-3}. A molecular H density of this magnitude is also observed (Beckwith, Persson, and Neugebauer 1979).

One interesting factor should still be mentioned. If the column density of molecular H in the KL Nebula is $\sim 3 \times 10^{20}$ cm^{-2} (Beckwith, Persson, and Neugebauer 1979) and the initial O abundance in the region was cosmic, then, allowing for the O now in the form of CO, the resulting column density of atomic O in the nebula is $\sim 4 \times 10^{17}$ cm^{-2}. Assuming a temperature of 1000 K and a density $n_{H_2} \sim 10^6$ cm^{-3}, the expected 63-μm flux would be be $\sim N_O Ah\nu/3$, where $A = 9 \times 10^{-5}$ s^{-1} is the Einstein coefficient, the energy per emitted photon is $h\nu = 3 \times 10^{-14}$ ergs, and the factor 1/3 accounts for the weight of different states. This assumes that the density of H_2 substantially exceeds the critical density. The expected flux then is of the order of 3×10^{-16} W cm^{-2}, well below the total for the Orion Nebula which Melnick, Gull, and Harwit (1979) observed, but well above the upper limit for the KL Nebula, 5×10^{-17} W cm^{-2}, found by Storey, Watson, and Townes (1979).

The Berkeley group (Storey, Watson, and Townes 1981) has also made a tentative detection of the $^2\Pi_{3/2}$, $J = 5/2 \rightarrow 3/2$ transition of OH, approximately 30" north of the KL Nebula. They calculate a column density of 3.6×10^{15} cm^{-2}

molecules of shocked OH. At a distance of 500 pc the number of molecules in a 1' beam then becomes 6×10^{50}. This still is very low compared to the amount of CO present. The other form in which O might be found is H_2O. Phillips et al. (1978), however, estimate typical water vapor concentrations in the KL Nebula to be $n_{H_2O}/n_{H_2} \sim 10^{-5}$. Dust grains alone also cannot contain the expected amount of O. The weakness of the 45-μm H_2O ice band recently reported by Erickson et al. (1981), as well as the upper limits on material required to produce the 3.28-μm emission feature that might be related to water on grains (Sellgren 1981), precludes significant amounts of O on grains. This leaves as a puzzle the whereabouts of O, unless it appears in the form of O_2, or CO_2 whose infrared spectrum might be observable, or unless C is more abundant than O in the gas in the KL Nebula.

Hill and Hollenbach (1978) have predicted strong atomic O emission in shocked neutral clouds surrounding H II regions. On the other hand, Iglesias (1977) finds that a dense molecular cloud cooling to 30 K becomes depleted of atomic O, largely at the expense of increasing amounts of O_2 and CO, during the course of 3×10^6 years. Iglesias and Silk (1978) have also studied the chemistry of regions that are shocked after an initial cool-down. The atomic O abundance remains low, but H_2O becomes almost as abundant as CO in the hot, postshocked gas. In fast shocks, however, these molecules are dissociated as shown by Hollenback and McKee (1980). The contrast between the prediction of Hollenbach, Hill, and McKee, on the one hand, and Iglesias and Silk on the other, holds out hope that observations of the kind discussed here may soon provide decisive data on the basis of which theoretical models can be supported or eliminated.

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